VERTICAL DISTRIBUTION OF STARS AND GAS IN A GALACTIC DISK

Chanda J. Jog
Indian Institute of Science, Bangalore 560012, India
cjjog@physics.iisc.ernet.in

Abstract   We study the vertical density distribution of stars and gas (HI and H_2) in a galactic disk which is embedded in a dark mater halo. The new feature of this work is the inclusion of gas, and the gravitational coupling between stars and gas, which has led to a more realistic treatment of a multi-component galactic disk. The gas gravity is shown to be crucially important despite the low gas mass fraction. This approach physically explains the observed scaleheight distribution of all the three disk components, including the long-standing puzzle (Oort 1962) of a constant HI scaleheight observed in the inner Galaxy. The above model is applied to two external galaxies: NGC 891 and NGC 4565, and the stellar disk is shown to be not strictly flat as was long believed but rather it shows a moderate flaring of a factor of ~ 2 within the optical radius.

1.   Introduction

The visible mass in a galactic disk is distributed in a thin disk, hence the planar and the vertical dynamics can be treated separately. The vertical distribution is not studied well unlike the planar mass distribution, though it is important to understand it since it acts as a tracer of the galactic potential and the disk evolution. The vertical distribution in a one-component, isothermal, self-gravitating disk was studied in a classic paper by Spitzer (1942). However, the physical origin of the thickness of stars and gas in a galactic disk and in particular their radial variation is not yet fully understood- we address this problem here.

In the past, gas gravity was often ignored even when studying the vertical distribution of gas, and the gas response to the stellar potential alone was considered. We show that stars and gas need to be treated jointly to get their correct vertical distribution. Due to its low velocity

dispersion, gas forms a thin layer and hence affects the dynamics and the vertical distribution of stars as well, despite the low gas mass fraction.

2.   Formulation of Three-component Model

The vertical scaleheight of HI gas in the inner Galaxy is remarkably constant which has been a long-standing puzzle (Oort 1962, Dickey & Lockman 1990). The vertical scaleheight is a measure of equilibrium between the gravitational force and the pressure. Hence the HI gas responding to the gravitational potential of an exponential stellar disk alone should show flaring, in contrast to the observed constant scaleheight.

We propose that an increase in the gravitational force due to the inclusion of gas can decrease the gas scaleheight, and study this idea quantitatively (Narayan & Jog 2002b). We formulate a general treatment where the stars, the HI gas and the H_2 gas are treated as three gravitationally coupled disk components, embedded in a dark matter halo. Thus each disk component experiences the same joint potential due to the three disk components and the dark matter halo, but each has a different response due to its different random velocity dispersion.

The equation of hydrostatic equilibrium along z or the vertical direction for each component and the joint Poisson equation are solved together. Thus each component obeys:

$$\frac{d^2\rho_i}{dz^2} = \frac{\rho_i}{<(v_z)_i^2>}\left[-4\pi G(\rho_s + \rho_{HI} + \rho_{H_2}) + \frac{d(K_z)_{DM}}{dz}\right] + \frac{1}{\rho_i}\left(\frac{d\rho_i}{dz}\right)^2$$

where i=1,2,3 denote the three disk components, and ρ_i and $<(v_z)_i^2>^{1/2}$ denote the mass density and the velocity dispersion respectively.

The above three coupled, second-order differential equations are solved numerically and iteratively, using $d\rho_i/dz = 0$ at the midplane and the observed mass surface density (Σ_i) as the two boundary conditions in each case. This results in a sech^2-like density profile for the mass density in each case, and we use its HWHM to define the vertical scaleheight.

Resulting Vertical Scaleheight vs. Radius

On using the joint potential, the HI scaleheight decreases as expected, and is in a better agreement with observations (Fig. 1), especially at large radii where the effect of gas gravity is higher because of the higher gas fraction. For H_2 gas, the joint potential gives a good agreement at all radii. In the stellar case, the joint potential gives a nearly flat curve that slowly rises with radius with a slope of 24 pc kpc^{-1} for 5-10 kpc, this agrees well with the near-IR observations (Kent et al. 1991).
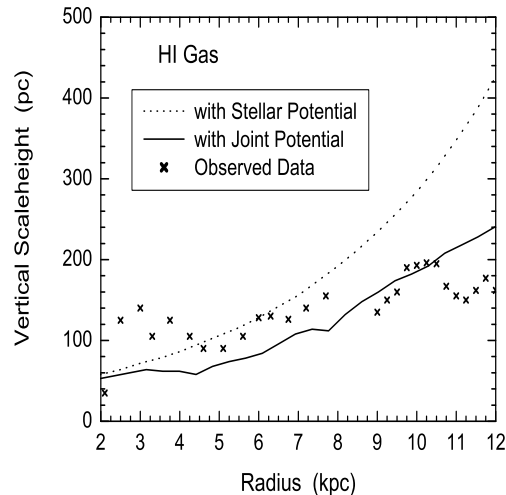
Figure 1. The joint potential gives a better fit to the HI data, and explains the constant HI scaleheight observed in the inner Galaxy. The agreement is even better for a slight linear increase in the HI velocity dispersion at small radii.

3.   Radially Increasing Stellar Scaleheight

We next applied this general model to two external, prototypical edge-on spiral galaxies: NGC 891 and NGC 4565, for which gas density values are known from observations - see Narayan & Jog (2002a) for details.

From the pioneering study of the vertical luminosity distribution of edge-on spiral galaxies, van der Kruit & Searle (1981a,b) concluded that the stellar vertical scaleheight in a galactic disk is constant with radius, and this is explained if the ratio $R_{vel}/R_d = 2$ where R_{vel} and R_d are the scalelengths with which the stellar velocity dispersion and disk luminosity fall off exponentially. This has been a paradigm in galactic structure for 25 years. However, there is no clear physical explanation for this. We argue that such a strict relation is unrealistic in general given the different sources of stellar heating now known to operate in a disk, such as heating via scattering off clouds or spiral arms within the galactic disk, and via heating due to tidal encounters with other galaxies.

Hence, our model is applied to NGC 891 and NGC 4565, treating the above ratio as a free parameter. The resulting stellar scaleheight is not strictly constant but instead shows flaring by a factor of ~ 2 within the optical radius (Fig. 2). This result agrees with observations (de Grijs & Peletier 1997). This is an important result for galactic structure.
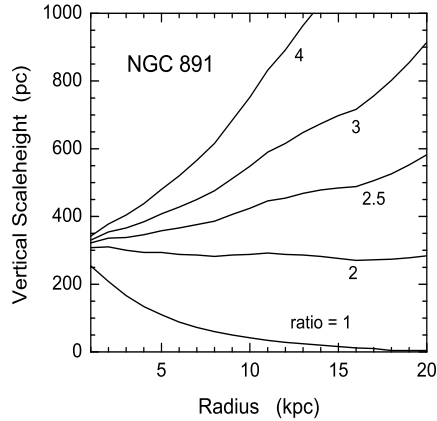
Figure 2. Resulting stellar vertical scaleheight vs. Radius: In general, the stellar scaleheight shows moderate flaring when the ratio $R_{vel}/R_d > 2$.

4. Conclusions

The multi-component approach developed here cohesively explains the observed vertical scaleheights of all the three disk components, namely the stars, the HI and the H_2 gas in the inner Galaxy.

The above model is applied to two external galaxies, NGC 891 and NGC 4565, and the resulting stellar scaleheight is shown to be not constant with radius, instead it shows flaring. Such a moderate increase in stellar scaleheight is likely to be common in other galaxies as well.

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